Mapping the Design Space of a Recuperated, Recompression, Precompression Supercritical Carbon Dioxide Power Cycle with Intercooling, Improved Regeneration, and Reheat

Andrew Schroder       Mark Turner

University of Cincinnati
Outline

- Overview of Supercritical CO$_2$ Power Cycles
- Proposed System Layout
- Variable Property Heat Engine Cycle Analysis Code
- Heat Exchangers with Nonlinear and Dissimilar Specific Heats
- Results of the Design Space Exploration
- Conclusions
About Supercritical CO$_2$ (S-CO$_2$) Power Cycles

- Closed loop configuration.
- Main compressor inlet temperature and pressure are at or near the critical point.
- Carbon dioxide is the proposed working fluid because it is cheap, inert, and has a critical temperature of 304K (31°C), which is near typical ambient temperatures of $\sim$ 294K (21°C).
- High system pressures occur due to the high critical pressure of carbon dioxide (7.4 MPa).
- Possible applications:
  - Base load terrestrial electrical power generation
  - Marine, Aviation, and Spacecraft electrical power generation
- Possible Configurations:
  - Bottoming cycle using waste heat from a traditional open loop gas turbine (traditional Brayton cycle)
  - Primary cycle with nuclear and solar energy heat sources
  - Primary cycle with the combustion of fossil fuels as a heat source
Supercritical CO$_2$ Power Cycle - Strengths

- Low Pressure Ratio (optimal overall pressure $\sim$ 3 to 8)
- Large amounts of recuperation possible.
- Low back work ratio
  - Decreased sensitivity of compressor/turbine efficiency on cycle efficiency.
  - S-CO$_2$ - $\sim$35%
  - Rankine - $\sim$2%
  - Open Loop Brayton - 40-80%
- High Power Density
  - High pressure and high molecular weight.
  - Fluid densities range from $\sim$23 kg/m$^3$ to $\sim$788 kg/m$^3$.
- Narrow heat addition and heat rejection temperatures does not require evaporative cooling, but still approximates a Carnot cycle better than an open loop Brayton cycle.
- High real cycle efficiency predicted
  - $>50\%$ @ 923K (650°C) turbine inlet temperature
Supercritical CO$_2$ Power Cycle - Weaknesses

- Nonlinear specific heat mismatch causes difficulties exchanging heat between high and low pressure sides at lower temperatures.
- Closed loop design presents additional system complexities.
- High pressures present increased structural loading and seal leakage issues.
  - 20MPa to 30MPa maximum pressure typically proposed
- Nonlinear property variations near the critical point present turbomachinery design complications as well as challenges maintaining off design operability.
- High working fluid densities prohibit efficient low power, low speed, low cost prototypes to be developed.
Proposed System Layout

- Three compressors and several flow splits are used to help mitigate heat transfer issues due to specific heat mismatches.
- Four shafts are utilized to better match optimal operating speeds of each turbomachinery component.
- Due to the small size of the turbomachinery, as well as the use of multiple shafts, each assembly (except for the power turbine and generator) can be placed inside a pressure vessel to avoid the need for high speed, high pressure seals.
- Tanks and a blow down startup procedure are used to eliminate the need to attach a motor to the higher speed shafts.
Proposed System Layout - Temperature Entropy Diagram

Cycle Efficiency: 51.94%
Line widths scaled by mass fraction.

Critical Temperature: 304.13K
Critical Pressure: 7.377MPa

Constant Pressure Lines
- 10.03MPa
- 10.00MPa
- 25.21MPa
- 25.16MPa
- 25.16MPa
- 25.16MPa
- 24.93MPa
- 14.65MPa
- 14.61MPa
- 5.84MPa
- 5.60MPa

$c_p$, Specific Heat at Constant Pressure [J/(kg*K)]
Proposed System Layout - Temperature Entropy Diagram

Cycle Efficiency: 47.31%
Line widths scaled by mass fraction.

Critical Temperature: 304.13K
Critical Pressure: 7.377MPa

Constant Pressure Lines
- 10.06MPa
- 10.00MPa
- 20.47MPa
- 20.39MPa
- 20.39MPa
- 20.19MPa
- 8.24MPa
- 8.18MPa
- 2.75MPa
- 2.52MPa
Variable Property Heat Engine Cycle Analysis Code

- Cycle analysis code created from scratch.
- Developed with Python, NumPy, SciPy, and matplotlib.
- Variable fluid properties are utilized.
  - i.e. \( h = h(T, p), c_p = c_p(T, p), s = s(T, p) \)
  - Fluid property data used from REFPROP
- Specialized 1-D counterflow heat exchanger model was developed to account for variable fluid properties, yet maintaining high solution speed.
- Cycle iteratively solved for unknown pressures.
- Inputs include maximum temperature, minimum temperature, compressor pressure ratios, turbomachinery component efficiencies, heat exchanger pressure drop, main compressor inlet pressure, and mass fraction for flow splits.
- Design space for the inputs is explored in parallel and can run on as many processors as are available.
Currently the code only supports gases and supercritical fluids. Liquids and liquid vapor mixtures are not yet supported.

Heat source currently modeled is that of a constant heat flux (i.e. solar) or a highly regenerated combustion system (heater efficiency is assumed to be 100%).

Pumping power for the ambient pressure side of the heaters and coolers are assumed to be low.
Heat Exchangers - Overview

- The current heat exchanger model assumes the limiting case where the convection coefficient is very high.
  - The temperature difference between the high pressure to the low pressure side of the heat exchanger is assumed to be purely due to specific heat mismatches.
  - At at least one point in the heat exchanger there will be approximately zero temperature difference between the high and low pressure side.

- Pressure drop
  - Pressure drop is not computed based on an assumed geometry, but is approximated to be linearly dependent upon temperature drop in the heat exchanger.
  - Temperature drop is assumed to be related to the length of the heat exchanger.
  - The linear relationship between temperature drop and pressure drop is another parameter varied as part of the design space exploration.
  - Pressure drop is assumed to be low, allowing the present approximation to be acceptable.
Heat Exchangers - Temperature and Specific Heat Variation

Cooled Side Inlet: Temperature=350.0K, Pressure=1.0MPa, Mass Fraction=1.00
Heated Side Inlet: Temperature=305.0K, Pressure=1.0MPa, Mass Fraction=1.00
Pressure Drop=0 Pa/K, Inlet Pressure Ratio=1.0, $\phi=1.00$

$\Delta T = T_{\text{Cooled}} - T_{\text{Heated}}, \text{[K]}$

Heat Capacity Ratio, $C_{\text{Heated}}/C_{\text{Cooled}}$
Heat Exchangers - Temperature and Specific Heat Variation

Cooled Side Inlet: Temperature=450.0K, Pressure=1.0MPa, Mass Fraction=1.00
Heated Side Inlet: Temperature=305.0K, Pressure=1.0MPa, Mass Fraction=0.60
Pressure Drop=5000 Pa/K, Inlet Pressure Ratio=1.0, φ=0.63

Temperature, Cooled Side, [K]

Heat Capacity Ratio, $\frac{C_{Heated}}{C_{Cooled}}$

$\Delta T = T_{Cooled} - T_{Heated}$, [K]
Heat Exchangers - Temperature and Specific Heat Variation

Cooled Side Inlet: Temperature=450.0K, Pressure=5.0MPa, Mass Fraction=1.00
Heated Side Inlet: Temperature=305.0K, Pressure=25.0MPa, Mass Fraction=1.00
Pressure Drop=5000 Pa/K, Inlet Pressure Ratio=5.0, φ=0.55

\[ \Delta T = T_{\text{Cooled}} - T_{\text{Heated}}, \text{[K]} \]

Heat Capacity Ratio, \( C_{\text{Heated}}/C_{\text{Cooled}} \)
### Design Space Exploration

**Dataset I - 20,155,392 permutations**

**All Parameters - Coarse Exploration**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Number of Values</th>
<th>Value Plotted</th>
</tr>
</thead>
<tbody>
<tr>
<td>PreCompressor Pressure Ratio</td>
<td>1.0</td>
<td>4.0</td>
<td>6</td>
<td>Optimal</td>
</tr>
<tr>
<td>Main Compressor Pressure Ratio</td>
<td>1.1</td>
<td>4.1</td>
<td>6</td>
<td>Optimal</td>
</tr>
<tr>
<td>Recompression Fraction</td>
<td>0.000</td>
<td>0.991</td>
<td>4</td>
<td>Optimal</td>
</tr>
<tr>
<td>Low Temperature Recuperator Main Fraction High Pressure Component Mass Fraction</td>
<td>0.001</td>
<td>0.991</td>
<td>4</td>
<td>Optimal</td>
</tr>
<tr>
<td>Main Compressor Inlet Pressure</td>
<td>6 MPa</td>
<td>10 MPa</td>
<td>6</td>
<td>Optimal</td>
</tr>
<tr>
<td>Maximum Temperature</td>
<td>798K</td>
<td>923K</td>
<td>3</td>
<td>923K</td>
</tr>
<tr>
<td>Minimum Temperature</td>
<td>320K</td>
<td>333K</td>
<td>3</td>
<td>320K</td>
</tr>
<tr>
<td>Main Compressor Isentropic Efficiency</td>
<td>0.75</td>
<td>1.00</td>
<td>4</td>
<td>0.85</td>
</tr>
<tr>
<td>PreCompressor Isentropic Efficiency</td>
<td>0.80</td>
<td>0.95</td>
<td>3</td>
<td>0.875</td>
</tr>
<tr>
<td>ReCompressor Isentropic Efficiency</td>
<td>0.80</td>
<td>0.95</td>
<td>3</td>
<td>0.875</td>
</tr>
<tr>
<td>Power Turbine Isentropic Efficiency</td>
<td>0.89</td>
<td>0.93</td>
<td>3</td>
<td>0.93</td>
</tr>
<tr>
<td>Main/Re/Pre Compressor Turbine Isentropic Efficiency</td>
<td>0.84</td>
<td>0.89</td>
<td>3</td>
<td>0.89</td>
</tr>
<tr>
<td>Heat Exchanger Pressure Drop</td>
<td>500 Pa/K</td>
<td>0 Pa/K</td>
<td>2</td>
<td>500 Pa/K</td>
</tr>
</tbody>
</table>
## Design Space Exploration

### Dataset II - 1,800,000 permutations

Fixed Component Efficiencies and Max/Min Temp, Other Parameters Refined

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Number of Values</th>
<th>Value Plotted</th>
</tr>
</thead>
<tbody>
<tr>
<td>PreCompressor Pressure Ratio</td>
<td>1.0</td>
<td>4.0</td>
<td>20</td>
<td>Optimal</td>
</tr>
<tr>
<td>Main Compressor Pressure Ratio</td>
<td>1.1</td>
<td>4.1</td>
<td>20</td>
<td>Optimal</td>
</tr>
<tr>
<td>Recompression Fraction</td>
<td>0.000</td>
<td>0.991</td>
<td>15</td>
<td>Optimal</td>
</tr>
<tr>
<td>Low Temperature Recuperator Main Fraction</td>
<td>0.001</td>
<td>0.991</td>
<td>15</td>
<td>Optimal</td>
</tr>
<tr>
<td>High Pressure Component Mass Fraction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Compressor Inlet Pressure</td>
<td>6 MPa</td>
<td>10 MPa</td>
<td>20</td>
<td>Optimal</td>
</tr>
<tr>
<td>Maximum Temperature</td>
<td>923K</td>
<td>923K</td>
<td>1</td>
<td>923K</td>
</tr>
<tr>
<td>Minimum Temperature</td>
<td>320K</td>
<td>320K</td>
<td>1</td>
<td>320K</td>
</tr>
<tr>
<td>Main Compressor Isentropic Efficiency</td>
<td>0.85</td>
<td>0.85</td>
<td>1</td>
<td>0.85</td>
</tr>
<tr>
<td>PreCompressor Isentropic Efficiency</td>
<td>0.875</td>
<td>0.875</td>
<td>1</td>
<td>0.875</td>
</tr>
<tr>
<td>ReCompressor Isentropic Efficiency</td>
<td>0.875</td>
<td>0.875</td>
<td>1</td>
<td>0.875</td>
</tr>
<tr>
<td>Power Turbine Isentropic Efficiency</td>
<td>0.93</td>
<td>0.93</td>
<td>1</td>
<td>0.93</td>
</tr>
<tr>
<td>Main/Re/Pre Compressor Turbine Isentropic Efficiency</td>
<td>0.89</td>
<td>0.89</td>
<td>1</td>
<td>0.89</td>
</tr>
<tr>
<td>Heat Exchanger Pressure Drop</td>
<td>500 Pa/K</td>
<td>500 Pa/K</td>
<td>1</td>
<td>500 Pa/K</td>
</tr>
</tbody>
</table>
Design Space Exploration Results - Dataset II

Cycle Efficiency vs PreCompressor and Main Compressor Pressure Ratios

Maximum Efficiency = 51.94%

Note: The white region in the lower left corner of the figure represents efficiencies ranging from 0.0 to 0.3.
Design Space Exploration Results - Dataset II

Optimal Recompression Fraction vs PreCompressor and Main Compressor Pressure Ratios
Design Space Exploration Results - Dataset II

Low Temperature Recuperator Main Fraction High Pressure Component Mass Fraction at Optimal Cycle Efficiency vs PreCompressor and Main Compressor Pressure Ratios
Design Space Exploration Results - Dataset II

Cycle Efficiency vs Recompression Fraction

![Graph showing the relationship between cycle efficiency and recompression fraction. The maximum efficiency is 51.94%.]
Design Space Exploration Results - Dataset II
Cycle Efficiency vs Main Compressor Inlet Pressure

Maximum Efficiency = 51.94%
Design Space Exploration Results - Dataset I

Cycle Efficiency vs Max and Min Temperature and Main and ReCompressor Efficiency

- **Maximum Temperature [K]:**
  - 780
  - 800
  - 820
  - 840
  - 860
  - 880
  - 900
  - 920
  - 940
  - Maximum Efficiency = 50.57%

- **Minimum Temperature [K]:**
  - 0.485
  - 0.490
  - 0.495
  - 0.500
  - 0.505
  - 0.510
  - Minimum Efficiency = 50.57%

- **Main Compressor Isentropic Efficiency:**
  - 0.500
  - 0.502
  - 0.504
  - 0.506
  - 0.508
  - 0.510
  - 0.512
  - Maximum Efficiency = 51.34%

- **ReCompressor Isentropic Efficiency:**
  - 0.498
  - 0.500
  - 0.502
  - 0.504
  - 0.505
  - 0.507
  - 0.508
  - Maximum Efficiency = 51.18%
Web Based Graphical User Interface

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Sensitivity Plots and Cycle Plot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dataset</td>
<td>20,155,392 permutations - All Parameters - Coarse Exploration</td>
</tr>
<tr>
<td>PreCompressor Pressure Ratio</td>
<td>Value for Maximum Efficiency</td>
</tr>
<tr>
<td>Main Compressor Pressure Ratio</td>
<td>Value for Maximum Efficiency</td>
</tr>
<tr>
<td>Recompression Fraction</td>
<td>Value for Maximum Efficiency</td>
</tr>
<tr>
<td>Low Temperature Recuperator</td>
<td>Value for Maximum Efficiency</td>
</tr>
<tr>
<td>Main Fraction High Pressure Component Mass Fraction</td>
<td>Value for Maximum Efficiency</td>
</tr>
<tr>
<td>Main Compressor Inlet Pressure [Pa]</td>
<td>Value for Maximum Efficiency</td>
</tr>
<tr>
<td>Maximum Temperature [K]</td>
<td>923.0</td>
</tr>
<tr>
<td>Minimum Temperature [K]</td>
<td>320.0</td>
</tr>
<tr>
<td>Main Compressor Isentropic Efficiency</td>
<td>0.85</td>
</tr>
<tr>
<td>PreCompressor Isentropic Efficiency</td>
<td>0.875</td>
</tr>
<tr>
<td>ReCompressor Isentropic Efficiency</td>
<td>0.875</td>
</tr>
<tr>
<td>Power Turbine Isentropic Efficiency</td>
<td>0.93</td>
</tr>
<tr>
<td>Main/Re/Pre Compressor Turbine Isentropic Efficiency</td>
<td>0.89</td>
</tr>
<tr>
<td>Heat Exchanger Pressure Drop [Pa/K]</td>
<td>500.0</td>
</tr>
<tr>
<td>Sensitivity Plot Dependent Variable</td>
<td>Plot Value for Maximum Efficiency</td>
</tr>
<tr>
<td>Maximum Cycle Efficiency</td>
<td>Contour Plot</td>
</tr>
<tr>
<td></td>
<td>Line Plot</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cycle Plot</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal Axis</td>
</tr>
<tr>
<td>None (loads quicker)</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td></td>
</tr>
<tr>
<td>Enthalpy</td>
<td></td>
</tr>
<tr>
<td>Entropy</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td></td>
</tr>
<tr>
<td>CompressibilityFactor</td>
<td></td>
</tr>
<tr>
<td>cp</td>
<td></td>
</tr>
<tr>
<td>gamma</td>
<td></td>
</tr>
</tbody>
</table>
Conclusions

- Supercritical CO$_2$ Power Cycles have the potential for efficiencies of 51.94% with a maximum heat source temperature of 923K (650°C) and a minimum coolant temperature of 320K (47°C).
- A new system layout has been presented which may help to eliminate some of the design challenges with supercritical carbon dioxide engines.
- Highly nonlinear fluid properties present significant challenges in cycle and component design.
- A cycle analysis code has been developed, along with a web based interface for interactively exploring the design space. These tools can be continually expanded and improved to better understand supercritical carbon dioxide power cycles.
Questions?

http://AndySchroder.com/CO2Cycle/